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DTED Integrity Monitoring Using Differential GPS and Radar Altimeter

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BIOGRAPHY

Maarten Uijt de Haag is an Assistant Professor of Electrical Engineering at Ohio University, Athens, Ohio and a Principal Investigator with the Ohio University Avionics Engineering Center. He earned his Ph.D. from Ohio University, and also holds a B.S.E.E. and M.S.E.E from Delft University of Technology, the Netherlands. His research areas cover GPS, LAAS development, and integration of GPS with inertial measurement units, GPS signal modeling, multi-dimensional image processing techniques, and the application of advanced digital signal processing techniques for navigation aids. Currently, Maarten is involved in Ohio University's Digital Terrain Elevation Data (DTED) terrain avoidance system development utilizing GPS and radar altimeter monitoring.

Steve Young has been a flight systems researcher at NASA's Langley Research Center in Hampton, Virginia, since 1987. Initially, he was a member of a research team focused on the design and development of highly reliable fault-tolerant computers applied to aerospace missions. Since 1993, he has been a principal investigator developing advanced surface movement guidance and control systems (A-SMGCS) that can support all-weather operations on airport surfaces while reducing the likelihood of runway incursion. Recently, he has focused on extending the Synthetic Vision (SV) system concept employed for the A-SMGCS research to all phases of flight to reduce the likelihood of Controlled Flight into Terrain (CFIT). He is also co-chair of an RTCA/EUROCAE committee that has been established to define minimum requirements for terrain, obstacle, and airport databases for aviation uses.

Robert Gray is an Assistant Professor of Engineering at Penn State University, Erie, PA and has been active in the navigation field since his enlistment in the USAF as an avionics inertial navigation & Doppler radar technician. Robert earned his B.S.E.E. and Ph.D. from The Ohio University and a M.S.E.E. in guidance and controls from the Air Force Institute of Technology. Gray's avionics background include: being responsible for the stellar-inertial navigation system for the RC-135S, "Cobra Ball," Shemya AB, Alaska; flight crew member, B-52/KC-135 bombing and navigation competition, McConell AFB, KS; inertial navigation & weapons systems maintenance for the F-4D, Wichita, KS; controls & displays systems engineer for the C-135 "Speckled Trout," Andrews AFB, MD; creating, traveling and teaching the initial USAF introduction to GPS systems course in many USAF locations worldwide; lead GPS systems and Kalman filter integration engineer for the F-16C/D aircraft, F-16 System Program Office, WPAFB, OH; original team member of the Avionics Systems and Integration Research Team (ASIRT), at the former Wright Laboratory, Avionics Directorate, WPAFB, OH; and Vice-Chairman of the ION, Dayton, OH. Gray's current research interests include optimizing the applications and utilization of digital terrain elevation data for such uses as reduction of controlled flight into terrain; and the use of advanced reliability engineering techniques for enhanced aircraft safety.

ABSTRACT

This paper discusses a real-time digital terrain elevation data (DTED) integrity monitor for Civil Aviation applications. Providing pilots with Synthetic Vision (SV) displays containing terrain information has the potential to improve flight safety by improving situational awareness and thereby reducing the likelihood of Controlled Flight Into Terrain (CFIT). Utilization of the DTED for flight-critical terrain-displays, however, requires a DTED integrity check and timely integrity alerts to the pilots in those cases where DTED may provide hazardous misleading information. The discussed integrity monitor checks the consistency between the sensed terrain profile as computed from DGPS and radar altimeter data and the terrain profile as given by the

DTED. Probability of agreement between these two profiles is used to monitor the DTED integrity. A case study to verify the integrity monitor's performance is presented based on data collected during flight testing performed by NASA at Asheville, NC.

I. INTRODUCTION

A Flight Safety Foundation study of 132 accidents that occurred between 1984 and 1993 revealed that 54 (41%) involved Controlled Flight Into Terrain (CFIT) [1]. This study and others like it suggest that CFIT accidents are a significant contributor to the overall accident rate. Several CFIT mitigation strategies are being pursued by both the government and private sectors. Further, Terrain Awareness and Warning Systems (TAWS) are being mandated by the FAA for nearly all aircraft [2]. However, it is important to note that TAWS is purely an advisory system.

Recently, the government has made significant research and development investments to further improve aviation safety including the reduction of CFIT. Three examples are NASA's Aviation Safety Program, the FAA's SafeFlight21 Program, and NIMA's Ron Brown Airfield Initiative.

Within NASA's aviation safety program, the synthetic vision project is working on the development of a system that provides the pilots with advanced display technology containing terrain information as well as other information about the external environment such as obstacles and traffic. The terrain information is available from digital terrain elevation models (DEMs) such as the Digital terrain Elevation Data (DTED) sets produced by NIMA. Various DEMs are also available and/or being developed by other agencies such as NASA, NGS, and USGS. Each DEM product has its own coverage area and error characteristics.

When utilizing terrain elevation databases in applications other than advisory systems, it is important to avoid display of misleading terrain information. This paper proposes the addition of a real-time integrity monitor to the terrain elevation database in order to reduce the probability of an undetected database error. An overview of the proposed system concept is depicted in Figure 1. Sensor information from DGPS and radar altimeter are used to generate a synthesized, or "sensed", elevation profile. This profile is compared to the elevation profile from the stored database and if there are inconsistencies between the two, an integrity alarm will be generated and presented to the pilot in some fashion (to be determined).

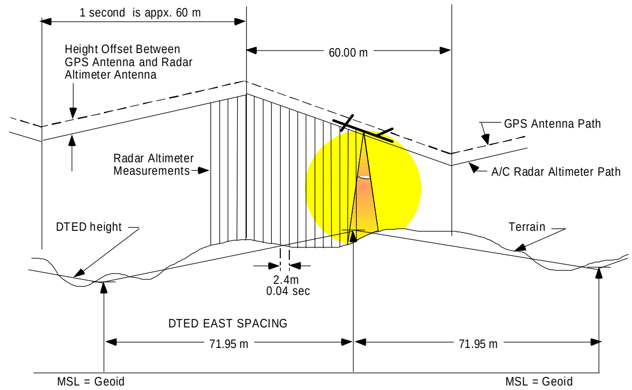


Figure 1. DTED terrain avoidance system concept

II. INTEGRITY MONITORING

The purpose of the integrity monitor for a Synthetic Vision System (SVS) is to provide the user with a warning when the SVS should be used with caution (or not to be used at all). Warnings would be provided when an error is detected that results in the display of hazardous misleading terrain information (HMTI) on the SVS display. The integrity is driven by the probability that the system does <u>not detect</u> the occurrence of this type of event. The probability of an undetected SVS failure is dependent on the probabilities of undetected failures in each of the SVS subsystems as depicted in the conceptual fault tree shown in Figure 2. For example, an SVS may consist of various components or subsystems such as the SVS display, the SVS computer, the terrain elevation database to generate the terrain, the obstacle database to generate the man-made objects that require visualization on the SVS display, navigation systems, etc. An undetected failure in each one of these subsystems can lead to a failure of the overall SVS. The SVS undetected failure rate is determined by the sum of the individual undetected failure rates ($P_{display}$, $P_{computer}$, $P_{terrain}$, $P_{obstacle}$, etc.). This is indicated by the "OR" operation in Figure 2.

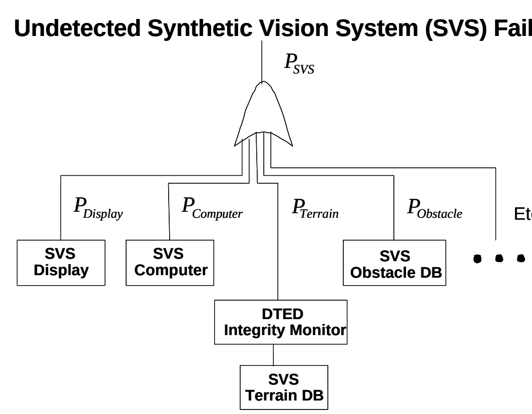


Figure 2. Sample Synthetic Vision System (SVS) Fault tree

This paper focuses on the DTED integrity monitor block depicted in Figure 2.

The required terrain elevation data (e.g. DTED) integrity level is dependent on the application of the SVS and the importance of the terrain elevation data within this application (i.e. the operational use of the SVS). In general, three categories of SVS applications are envisioned [3]:

1. SVS advisory system applications. The synthetic vision systems are non-essential and there is a reasonable probability of an undetected failure (integrity failure) with such a system. For these applications, there is a very low probability when using corrupted data that the continued safe operation of an aircraft would be at risk.
2. SVS strategic applications. The synthetic vision systems essential and the probability of an undetected failure (integrity failure) with such a system should be remote because the event will have serious impact on the aircraft and occupants. For these applications, corrupted data may place continued safe operation of an aircraft at risk.
3. SVS tactical applications. The synthetic vision systems are critical and the probability of an undetected failure (integrity failure) should be extremely improbable because the event will have catastrophic results for aircraft and occupants. For these applications, there is a high probability when using corrupted critical data that the continued safe operation of an aircraft would be severely at risk with potential for catastrophe.

The integrity levels required for these three types of applications are determined by their probability of an undetected failure. For advisory system applications, this probability can be greater than 10^{-5}. For strategic essential applications, this probability is expected to be between 10^{-5} and 10^{-9}. For flight-critical, SVS tactical applications, the level of integrity is expected to be smaller than 10^{-9}.

To avoid presenting HMTI to pilots, the integrity of the elevation database needs to be monitored. HMTI monitoring is based on checking the agreement, or consistency, between the stored digital terrain elevation data and elevation data derived from an independent source (e.g. synthesized terrain). The digital terrain elevation database can be any DEM (such as DTED I). The synthesized terrain in our case is computed from sensor information from Differential GPS (DGPS) and radar altimeter. Example DGPS implementations that may be used are kinematic GPS (KGPS), the Local Area Augmentation System (LAAS), or the Wide Area Augmentation System (WAAS).

The metrics used to express the degree of agreement between the synthesized and database terrains are the absolute and successive disparities [4,5]. The absolute disparity is given by:

$$p(t_i) = h_{SYNT}(t_i) - h_{DTED}(t_i) \qquad (1)$$

where h_{SYNT} is the synthesized height and h_{DTED} is the height as derived from the terrain elevation database. Both elevations are defined at time t_i. In the proposed system the synthesized height is given by the difference between the height above Mean Sea Level (MSL) as derived from DGPS, h_{DGPS}, and the height Above Ground Level (AGL) as obtained from the radar altimeter, h_{RADALT}, according to:

$$h_{SYNT}(t_i) = h_{DGPS}(t_i) - h_{RADALT}(t_i) \qquad (2)$$

The successive disparity is given by:

$$s(t_i) = p(t_i) - p(t_{i-1}) \qquad (3)$$

Successive disparities have been used extensively in military systems. The main advantage of subtracting the previous absolute disparity from the current absolute disparity is the ability to remove radar altimeter biases. However, for the design of an integrity monitor, this bias removal feature can be undesirable, because it can cause bias-like errors in the terrain elevation database to be missed.

For the implementation of an integrity monitor, test statistics are derived based on absolute and successive disparities. Test statistics are indicators or measures of agreement based on the systems' nominal performance. If this test statistic exceeds a pre-defined threshold, an integrity alarm results. Computation of these thresholds requires an understanding of the underlying system fault mechanisms and characterization of the nominal system error performance described by the probability density functions (PDFs) of both the terrain elevation database errors and errors in the sensor(s) used to derive the synthesized elevations.

Three possible test statistics are described in [6]: the mean squared difference (MSD), the mean absolute difference (MAD), and the cross-correlation (XCORR). The mathematical expressions for these test statistics are given in table 1.

	Absolute Disparity	Successive Disparity	Elevation
MSD	$\frac{1}{N}\sum_{i=1}^{N} p^2(t_i)$	$\frac{1}{N-1}\sum_{i=2}^{N} s^2(t_i)$	X
MAD	$\frac{1}{N}\sum_{i=1}^{N} \lvert p(t_i)\rvert$	$\frac{1}{N-1}\sum_{i=2}^{N} \lvert s(t_i)\rvert$	X
XCOR	X	X	$\frac{1}{N}\sum_{i=1}^{N} h_{SYNT}(t_i)\cdot h_{DTED}(t_i)$

Table 1. Possible test statistics

Of these three functions, [6] has shown that the MSD outperforms both the MAD and XCORR functions for terrain correlation applications.

The summations in table 1 are over N absolute or N-1 successive disparities. Therefore, N can be interpreted as an integration time. [4] shows the performance of the integrity monitor for a variety of values for N. For the case study presented later in this paper, N is chosen to be 50.

To enable computation of the test statistic thresholds under fault free or nominal conditions, the underlying error PDFs need to be determined. An initial investigation showed that the absolute disparities are distributed according to $N(0,(18.9)^2)$ and the successive disparities are distributed according to $N(0,(13.0)^2)$ for DTED I.

T is the test statistic given by a scaled MSD of the absolute disparities (MSD_{ad}). Z is the test statistic given by the scaled MSD of the successive disparities (MSD_{sd}). Based on the given underlying normal distributions of the absolute and successive disparities, T is found to be a chi-square distribution with N degrees of freedom [4] and Z is found to be a normal distribution for N > 20 [4]. Based on these PDFs, and an a priori probability of agreement (between the synthesized and database elevation profile [4]), P_a, appropriate thresholds can be calculated. Within the context of this paper P_a was chosen to be 0.9999, and the integration time was chosen to be N=50. A limited integration time of 50 seconds limits the time required to achieve confidence in the database. Based on these values, the threshold for the T was found to be equal to $T_{threshold}$ = 96 and the threshold for Z was found to be equal to $Z_{threshold}$ = 2.2 for the case study presented in this paper.

III. DIGITAL ELEVATION MODELS

Elevation databases that may be used to generate the synthetic vision displays, are referred to as digital elevation models (DEMs). A variety of sources provide DEMs specified by a number of parameters, such as the post-spacing or resolution, the horizontal and vertical references or datums, and the circular and linear errors. The circular error represents the horizontal accuracy specification on the post position, whereas the vertical error specifies the accuracy in the vertical direction (height) [6]. The circular and vertical errors are depicted in Figures 3 and 4, respectively.

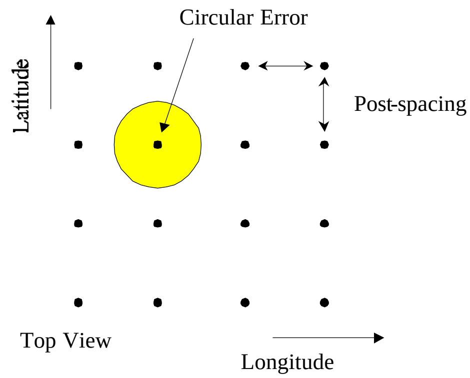


Figure 3. Digital Elevation Models Circular Error

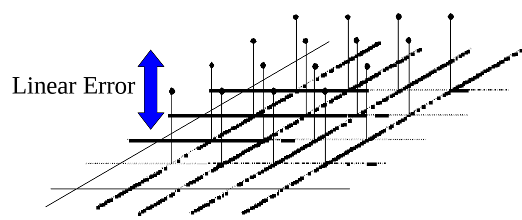


Figure 4. Digital Elevation Model Vertical Error

Various DEMs were available for the Asheville, NC area to support our case study analysis. These include the Airport Safety Modeling Data (ASM100 and ASM12), the Digital Terrain Elevation Data (DTED level I and DTED level II) [8], the United States Geological Survey (USGS) DEM, and a high resolution National Geodetic Survey (NGS5) DEM created solely for the Asheville airport area. Table 2 gives an overview of the characteristic parameter values for these databases.

	Post Spacing	CEP	LEP	Horizontal Datum	Vertical Datum	Segment Size
DTED I	3 arc-sec	<50m, 90%	<30m, 90%	WGS84	MSL	1^o x 1^o
DTED II	1 arc-sec	<50m, 90%	<30m, 90%	WGS84	MSL	1^o x 1^o
USGS	3 arc-sec (v)	N/A	N/A	WGS84	NGVD27	1^o x 1^o (v)
ASM100	15 arc-sec	<50m, 90%	(*)	WGS84	MSL	100 nmi x 100 nmi
ASM12	6 arc-sec	<50m, 90%	(*)	WGS84	MSL	12 nmi x 12 nmi
NGS5	5 m	1m, 90%	1m, 90%	WGS84	MSL	8.8 nmi x 3 nmi

Table 2. Digital Elevation Models (DEMs)

The ASM100 and ASM12 elevation databases have a 15 and 6 arc-sec post spacing and are derived from DTED level I elevation data. The elevation for each of the posts was defined as the maximum height of all surrounding posts in the DTED I. The ASM data sets are publicly available from NOAA for terrain-impacted airports. DTED level I and II are NIMA products that are not publicly available that have been produced to support military missions by DoD. The USGS DEM is publicly available.

The Shuttle Topography Mission, which was flown in January 2000, will provide us with another DEM. This Shuttle mission mapped the surface of the Earth between plus and minus 60 degrees latitude (approximately). The main advantage of this DEM will be the fact that the characteristics (errors) should be consistent across the DEM as it comes from a single source. Other "world- DEMs historically come from multiple sources and are "patched" together.

IV. INTERPOLATION ISSUES

Typically, DEMs are two-dimensional discrete representations of the three-dimensional terrain. The proposed integrity monitor requires the knowledge of points in between the discrete latitudes and longitudes. To compute these elevations interpolation methods are used. The method used in our proposed scheme is the bilinear interpolation described in [9] and given by:

$$\begin{aligned} h_I(j, l) = &(1-\Delta_l)(1-\Delta_j)h_1(j_{SW}, l_{SW}) + \\ &(1-\Delta_l)\Delta_j h_2(j_{NW}, l_{NW}) + \\ &\Delta_l(1-\Delta_j)h_3(j_{SE}, l_{SE}) + \\ &\Delta_l \Delta_j h_4(j_{NE}, l_{NE}) \end{aligned} \tag{4}$$

where h_1 through h_4 are the elevations of the surrounding locations, and the relative distances from the south-west (SW) point are given by:

$$\begin{aligned} \Delta_l &= \frac{l - l_{SW}}{l_{SE} - l_{SW}} \\ \Delta_j &= \frac{j - j_{SW}}{j_{NW} - j_{SW}} \end{aligned} \tag{5}$$

where (j, l) is the latitude and longitude of the location for which the elevation needs to be computed, (j_{SW}, l_{SW}) is the position of the South West (SW) point, (j_{NW}, l_{NW}) is the location of the North West (NW) point, and (j_{SE}, l_{SE}) is the location of the South East (SE) point. Figure 5 illustrates the meaning of the parameters.

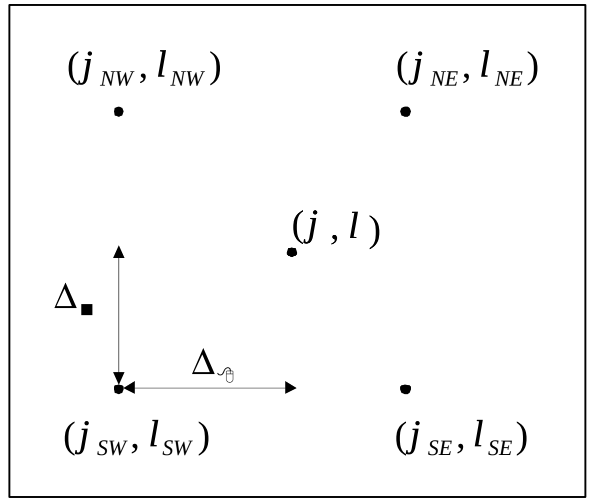


Figure 5. Bilinear Interpolation

V. FLIGHT TEST OVERVIEW

Flight tests were performed in the vicinity of the Asheville, NC, airport (AVL) during the fall of 1999 using an Air Force Convair aircraft known as the Total In-Flight Simulator (TIFS)[1]. The test was part of a research program led by NASA Langley Research Center investigating Synthetic Vision Systems (SVS). Figure 6 shows the TIFS on the ramp at AVL. Because of its forward flight deck, the TIFS aircraft provides a unique environment for flight-testing advanced avionics that drive experimental displays.

Figure 6. Total In-Flight Simulator (TIFS) aircraft

[1] TIFS is operated by Veridian Engineering, Buffalo, NY.

Figure 7. Forward flight deck with SVS displays

For the AVL flight-test a large active matrix LCD (19"x38") was installed in the TIFS forward flight deck. The LCD viewing area was split into two halves; the top half shows a camera image of the external environment and the bottom half shows the synthetic or "virtual" depiction of the external environment (Figure 7). Terrain was depicted using DEMs provided by NIMA, NOAA, and NGS. Obstacles (such as radio towers) were depicted using an obstacle database provided by NOAA. Traffic was also displayed along with the typical flight symbology such as pitch, roll, heading, altitude, and airspeed. In total, three evaluation pilots flew 53 approaches at AVL using the SVS display for primary tactical guidance cues.

Figure 8 is a top-level diagram of the experimental SVS employed on TIFS. The important components with respect to database integrity monitoring are the GPS components, the radar altimeter, and the geospatial data. Ashtech Z-12 GPS receivers were utilized both onboard and at the ground reference site. Post-processing of the recorded GPS data resulted in an accurate estimated flight trajectory ("truth") that has been used in the analysis presented. The nominal accuracy of this position data is 10 cm (RMS). The differentially-corrected GPS data that was filtered with INS data to provide real-time position updates to the display system has not been used for the integrity monitor assessment. Its nominal accuracy was on the order of 1-3 m (RMS).

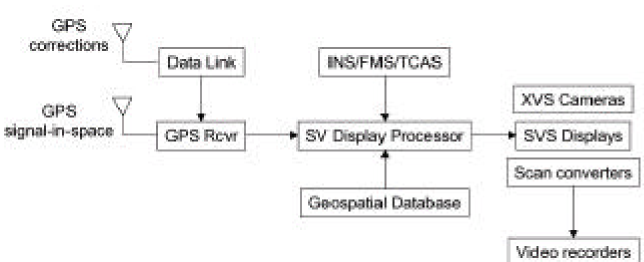


Figure 8. Top-level SVS architecture on TIFS

The radar altimeter used during the SVS test, was a Honeywell AN/APN-171(V) unit. Under standard conditions its altitude accuracy is given by:

$$\begin{aligned} e_{radalt} &= f(range, range\,rate) \\ &= 5 + 0.03 \cdot (range) + 0.05 \cdot (range\ rate) \quad ft \end{aligned} \tag{6}$$

Note that the radar altimeter error is a function of the altitude (range) and the rate at which the altitude changes (range rate). This altitude dependency needs to be included in the proposed integrity algorithm or avoided by overbounding the radar altimeter error PDF for all altitudes.

Finally, the geospatial database utilized during the flight tests resulted from merging several databases. Merging was required to account for different types of data (terrain, obstacles, and features) and also to account for varying degrees of granularity (of the terrain data). The SVS database design philosophy with respect to terrain databases is that greater terrain resolution will be required near airports (terminal areas). This is consistent with evolving RTCA and ICAO requirements.

VI. FLIGHT TEST RESULTS

The proposed test statistics were calculated for a number of flight segments flown in October 1999 with the TIFS. The set of flight segments includes one holding pattern at an altitude of ~650m and several Instrument Landing System (ILS) approaches to runway 16 and 34. Figure 9 shows the two-dimensional elevation model of the Asheville area using DTED level I. The runway and runway ends are illustrated as well as the holding pattern.

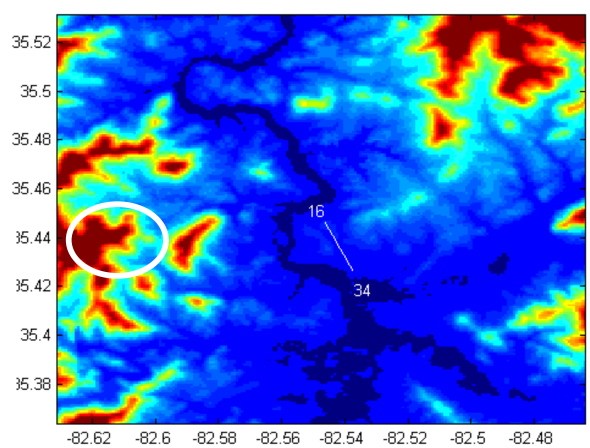


Figure 9. Digital Elevation Database for AVL

The ILS approach to runway 34 shows a different terrain profile than the approach to runway 16. During the initial approach to runway 34 the terrain is characterized by large variations, but during final approach the terrain variations become significantly smaller. During the approach to runway 16, the frequency of undulations in the terrain remains significant until the aircraft reaches the runway. Both characteristics can be observed in Figure 10.

Figures 10 and 11 show the altitude as measured by the radar altimeter during ILS approaches on runway 34 and 16, respectively. The figures furthermore show the difference between the KGPS elevation above MSL and the elevations derived from the ASM, DTED I, and USGS databases.

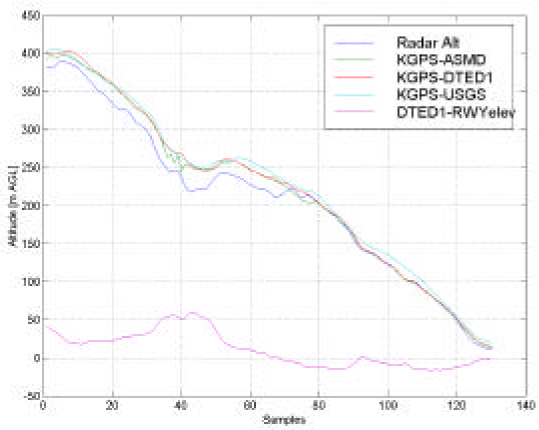


Figure 10. ILS Approach to Runway 34
(10/11/99 75047-75176)

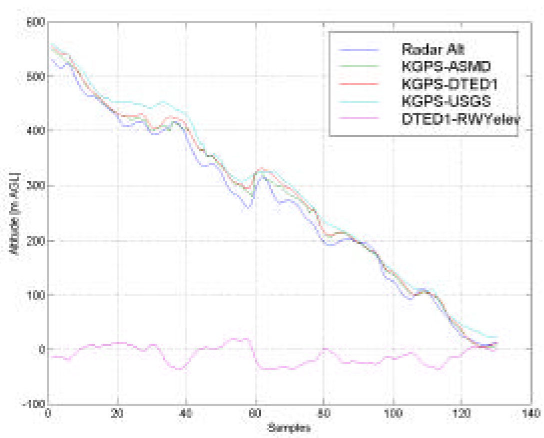


Figure 11. ILS Approach to Runway 16
(10/11/99 79040-79169)

Figures 12 and 13 show both the synthesized height and the database elevations in one figure for the same approaches as figures 10 and 11.

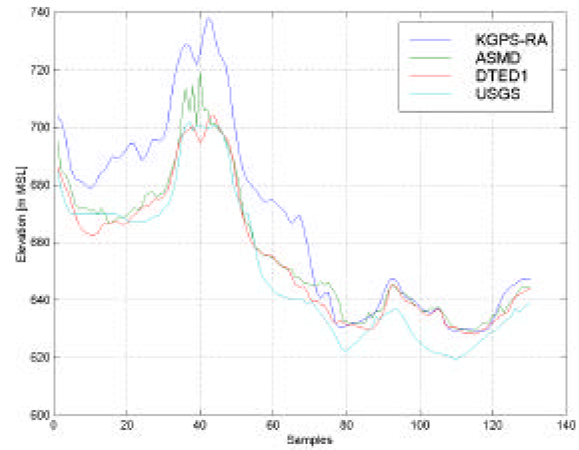


Figure 12. Database Profile to Runway 34
(10/11/99 75047-75176)

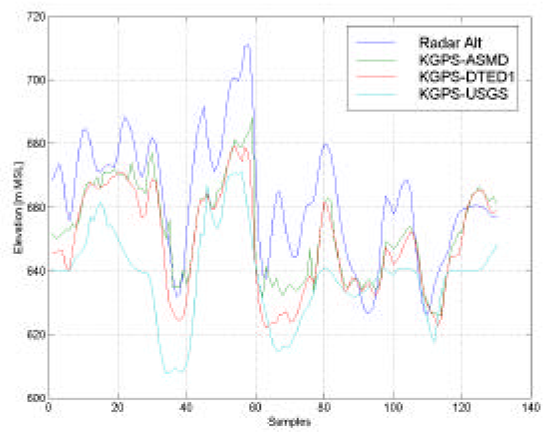


Figure 13. Database Profile to Runway 16
(10/11/99 79040-79169)

Figures 10 through 13 clearly show an inconsistency between the synthesized and database elevations. This inconsistency is more obvious when plotting the absolute disparities. Figures 14 and 15 show the absolute disparity for the approaches to runway 34 and 16, respectively. Significant biases show up in the absolute disparities. When causing an alert such a bias would be blamed on the terrain elevation database. However, during this test un-modeled radar altimeter errors could be causing the bias as well. During the approach on runway 34, the bias is present during flight over the terrain with large variations, and reduces to zero during final approach. The relationship between the low-frequency error component and the variation in the terrain may point to error mechanisms in the radar altimeter.

Another effect to be noted in Figures 14 and 15 is difference between the absolute disparities computed using the ASM and DTED I and the absolute disparities computed using the USGS. The fact that the ASM was derived from DTED I explains this discrepancy. It will be necessary to investigate the difference between DTED and USGS more closely. Different vertical datums and the use of different sources (remote sensing, photogrammetry, etc.) to derive terrain elevation information is the most likely explanation.

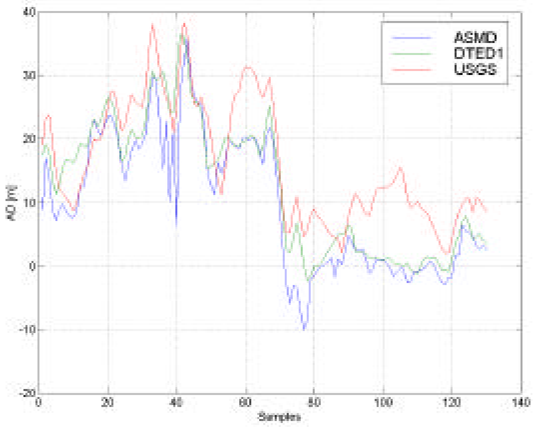


Figure 14. Absolute Disparities (AD) approaching Runway 34 (10/11/99 75047-75176)

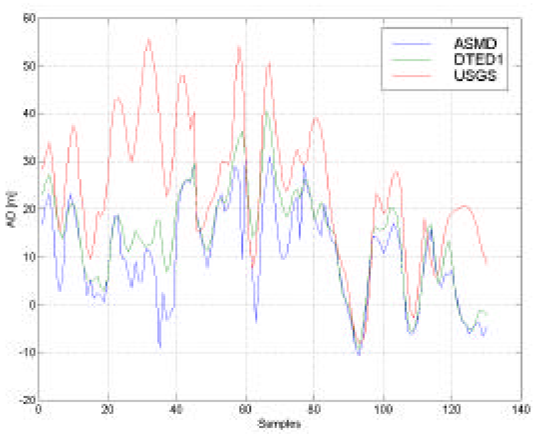


Figure 15. Absolute Disparities (AD) approaching Runway 16 (10/11/99 79040-79169)

To determine the effect on the test statistics, T and Z were calculated for two approaches to runway 16, one approach to runway 34, and the holding pattern. Figures 16 and 17 show the results for T and Z, respectively (th = $T_{threshold}$). As can be seen in figure 16, the presence of the bias does not cause the T statistic to exceed the threshold for the approach to runway 34. Removal of the bias, however, will improve the performance of the algorithm as is illustrated. Figure 16 also illustrates a violation of the threshold for one of the approaches to runway 16.

Note that while the aircraft was in the holding pattern over significant terrain, the threshold was exceeded continuously. Although this violation was caused by the same bias error, it may not be necessary to use the same threshold while at altitude as for approaches (or low altitude operations) because the SVS may not be a critical element of the operation at altitude (e.g. en-route).

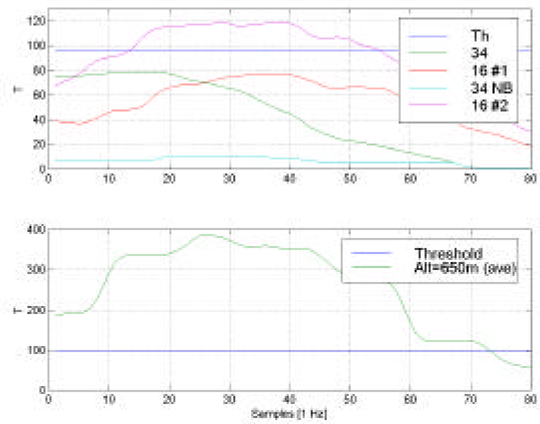


Figure 16. T Statistic, Pa= 0.9999, N= 50

Using the Z test statistic (see Figure 17), none of the flight segments caused Z to exceed the threshold due to Z's insensitivity to bias-like or low-frequency errors. This insensitivity of the Z statistic to biases is obvious from equation 3 and can be undesirable for an integrity monitor.

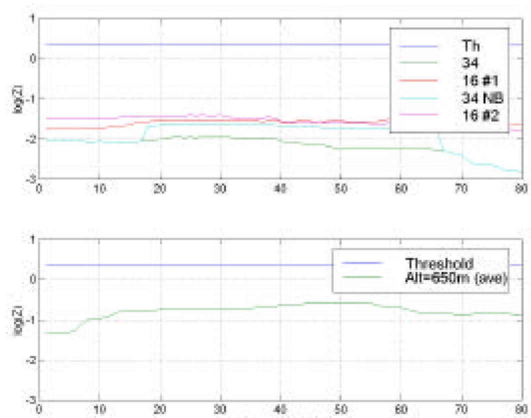
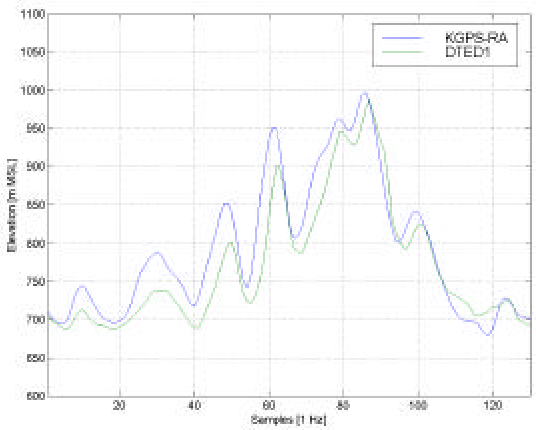


Figure 17. Z Statistic [log(Z)], Pa= 0.9999, N= 50

For the holding pattern and the approach to runway 16 that caused T to exceed the threshold, the synthesized and database elevations are given in Figures 18 and 19.

Although clearly present, the bias is not a constant and shows a strong dependence on the terrain features. Again, this can be caused by both inaccuracies in the radar altimeter measurements and errors in the database.



Database Profile West of Runway 34
(10/14/99 69189-69318)

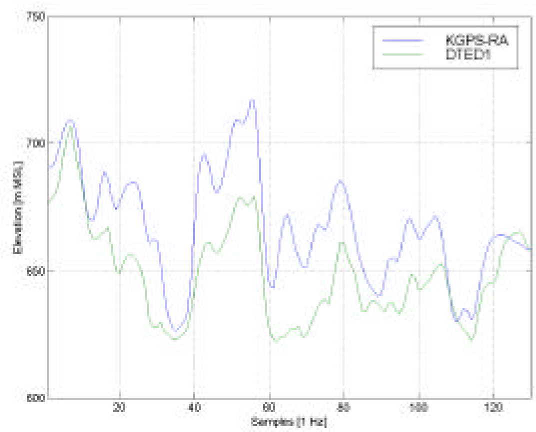


Figure 19. Database Profile to Runway 16
(10/14/99 67313-67442)

To investigate the relationship between the apparent biases and the terrain, all approach paths were plotted onto the terrain map of the Asheville area. Figure 20 shows the approaches during which the T threshold was not exceeded. Figure 21 shows the approaches during which the threshold was exceeded.

Note that numerous approaches to runway 16 triggered an integrity alert (exceeded the predefined threshold). Although it is difficult to indicate an exact cause, the terrain underneath these approaches is characterized by strong gradients in the terrain and the presence of water (i.e. a river). It is important to perform more analyses on the radar altimeter's behavior under these conditions and to repeat this type of assessment with alternate altimeters.

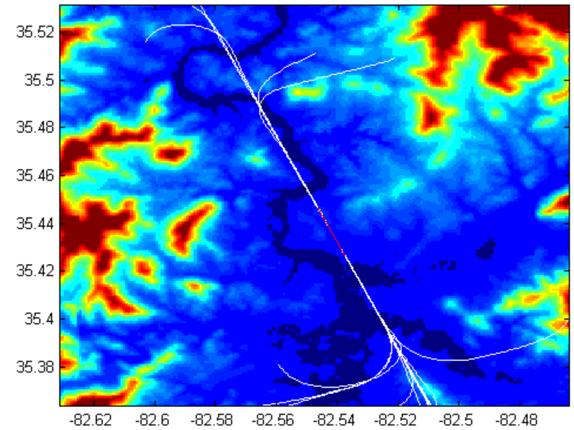


Figure 20. Approaches during which the threshold was not exceeded.

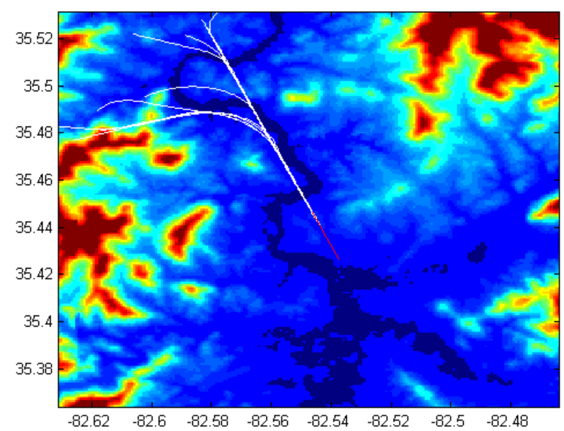


Figure 21. Approaches during which the threshold was exceeded.

VII. SUMMARY, CONCLUSIONS, AND FUTURE WORK

Flight tests were performed in the vicinity of Asheville, NC during which radar altimeter and KGPS data was collected. This data was combined with terrain elevation data originating from DTED I, the USGS DEM, and ASM12. Synthesized elevations were formed from the sensor information. Comparisons of the synthesized elevations with the elevations derived from the terrain databases show the presence of significant biases over terrain that has large variations. These biases may be due to elevation database or radar altimeter characteristics. In the absence of the bias, the variation in the absolute disparity is similar to the one previously shown in [4,5].

When implementing the test statistics T and Z, it was shown that Z was not sensitive to bias or low frequency errors due to the use of successive differences to compute this test statistic. Although larger than normal, most T values did not exceed the thresholds. Removal of the bias, however, showed a significant improvement in algorithm performance.

The T threshold was exceeded on various occasions during the approaches to runway 16. This may be due to inaccuracies in the terrain database, but it can also be attributed to error mechanisms of the radar altimeter. This requires a better characterization of the radar altimeter error mechanism. A verification of these findings is planned in Asheville, NC using Ohio University's DC-3 and an alternate radar altimeter.

Evaluation of the integrity algorithm for a variety of databases needs to be performed to observe the consistency among databases from several sources. This investigation will include terrain elevation data from the January 2000 Shuttle radar topography mission, the NGS 5m DEM, and DTED II.

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